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THE THERMAL RAM
A NEW CONCEPT FOR LOAD APPLICATION

By

W. H. Horton
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January 1969

U. S. ARMY AVIATION MATERIEL LABORATORIES
FORT EUSTIS, VIRGINIA

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This program was carried out under Contract DA 44-177-AMC-115(T) with Stanford University.

The report describes a novel approach to machine design for instability studies. The versatile machine is based on the thermal expansion principle.

The report has been reviewed by the U.S. Army Aviation Materiel Laboratories and is considered to be technically sound. It is published for the exchange of information and the stimulation of future research.

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THE THERMAL RAM, A NEW CONCEPT FOR LOAD APPLICATION

Final Report

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ABSTRACT

This report describes how thermal expansion of a block of material can be adapted to produce a versatile machine for instability studies. It indicates novel approaches to the creation of boundary conditions and non-uniform loading actions.

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INTRODUCTION

An experimentalist considering the uncertain nature of our knowledge with regard to the basic physics of cylindrical shell instability under the action of axial compressive force must recall the remark of Fourier: "Primary causes are unknown to us but are subject to simple laws which may be discovered by observation - the study of them being the object of natural philosophy". Of course, in this context, observation becomes not a seeing, not a sense, but measurements and active processes involving complicated mathematical systems of coordinates, delicate instruments and innumerable corrections.

We cannot, however, exclude from our considerations mathematical conjecture and analysis. The development of our knowledge must depend upon an interplay among observation, deduction and induction. For the particular problem referenced, however, there seems little doubt that the structure must, at this stage, be looked upon as a device which solves its own differential equations. Proper instrumentation and loading actions are, however, required to bring out the results.

The purpose of this report is to describe a development in loading systems which has been made in connection with stability investigations.

REQUIREMENT FOR LOADING ACTIONS

If the investigation of the instability of a compressed shell is regarded as a series of studies of quasi-static equilibrium states, then the appropriate loading action may be defined as follows: a need to produce and maintain, in a stable fashion, prescribed states of stress and strain-this need being associated with the important condition that the change from one state to another shall be varied in a smooth, controlled fashion. Of course, in satisfying this prime requirement, one must also bear in mind that additional secondary constraints may also result from the fact that the loading device and the necessary instrumentation for problem evaluation must be considered as a system. From this cause, then, there arises an additional desideratum: specifically, system stiffness. This need does not originate from the influence of machine stiffness on the stability action, (Ref. 1) as such, but rather from the need to avoid motions which will interfere both with the process of measurement and the load distributions.

In general, current test machines are hydraulically operated, although a limited number of screw jack and bellows-type machines can be found. Machines of these types are extremely difficult to control at very low loading rates, no matter how refined a control system is adopted. Additionally, in the piston-type devices, problems of rock are common. This is also true in bellows-type machines, although in some respects, loading control is easier.

The research described was aimed at improving this situation. A novel concept was developed. In this new loading process, force is produced as a consequence of controlled thermal expansion. For the sake of brevity, the loading element is termed a thermal ram.

THE THERMAL RAM PRINCIPLE

When a solid unrestrained block of metal is raised in temperature, it expands uniformly in all directions. The increase in linear dimension is a direct function of the temperature and the expansivity of the material. Generally speaking, the coefficient of linear expansion of metals is a very small quantity, of the order 10^{-5} inches/in/°F and so, of course, the extension per unit temperature rise is likewise small. If the free expansion of the material with increase in temperature is restricted, then work must be done to prevent the lineal or volumetric change and, so, force is produced.

The advantages which can accrue from using this basic principle of load generation are readily seen. They are as follows:

(1) Since temperature and heat flow can be readily and simply controlled with precision, any small rate of end shortening may be achieved.
(2) The thermal expansion device can have extreme rigidity.
(3) The normally expensive machining and lapping processes required to produce a hydraulic ram are not needed to produce a thermal ram. The material can be virtually ex-stock.
(4) The test machine control system is very simple and to all intents and purposes can be adapted from standard laboratory control systems.

The principle discussed above finds many applications. It can be used in every respect like a normal hydraulic jack provided the displacements required are not large.

APPLICATION TO TESTING OF CIRCULAR CYLINDERS UNDER AXIAL COMPRESSION

The first application made was in the testing of circular cylindrical shells under axial compression when studies of buckle populations were being conducted. Research by Horton and Durham,(Ref. 2) had shown that when a cylinder restrained by a mandrel (see Figure 1) is compressed, the shell can be completely filled with elastic buckles provided the gap between the mandrel and the shell is correctly dimensioned (Figure 2). This population of buckles was found to follow a normal population law, and the point of maximum buckle generation was found to correspond to the classic load value. In performing tests of this type, the difficulty lies in maintaining the loading action constant during the counting. Cox,(Ref. 3) found that this problem was much simplified by the use of the thermal ram. This was used as an auxiliary load device in a standard test machine (Figure 3). A typical result for a case of combined flexure and compression is given in Figure 4. In this particular application, the thermal ram used was a block of aluminum 3 inches in diameter and 6 inches long. The heater was a cartridge element of 500 watts capacity which was inserted into the block as shown in Figure 5. The control system was a simple on-off type, and the operation was always conducted at a very low level of heat input.

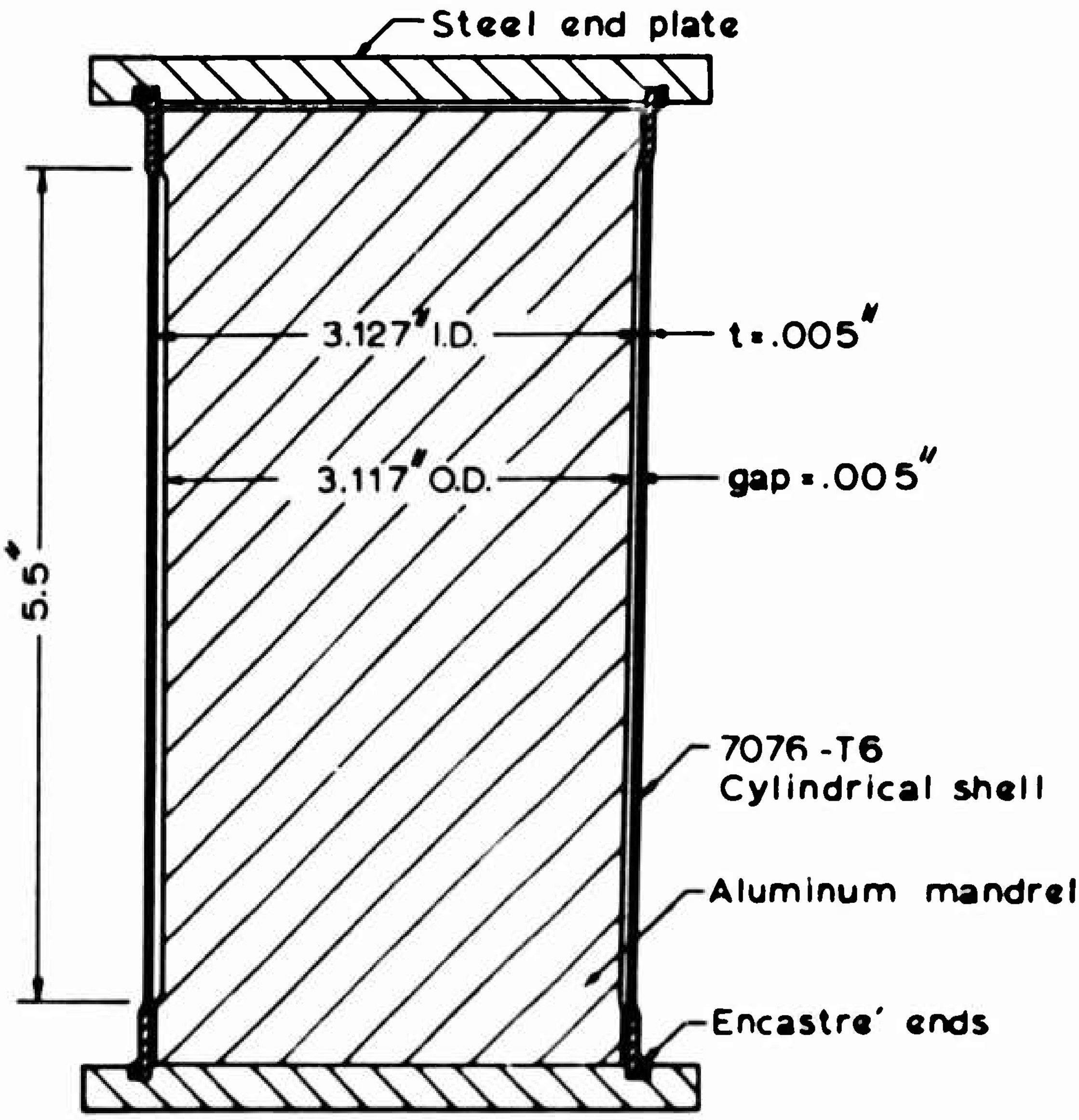

Figure 1. Typical Arrangement for Testing a Cylindrical Shell with Depth of Buckle Restricted by an Internal Mandrel.

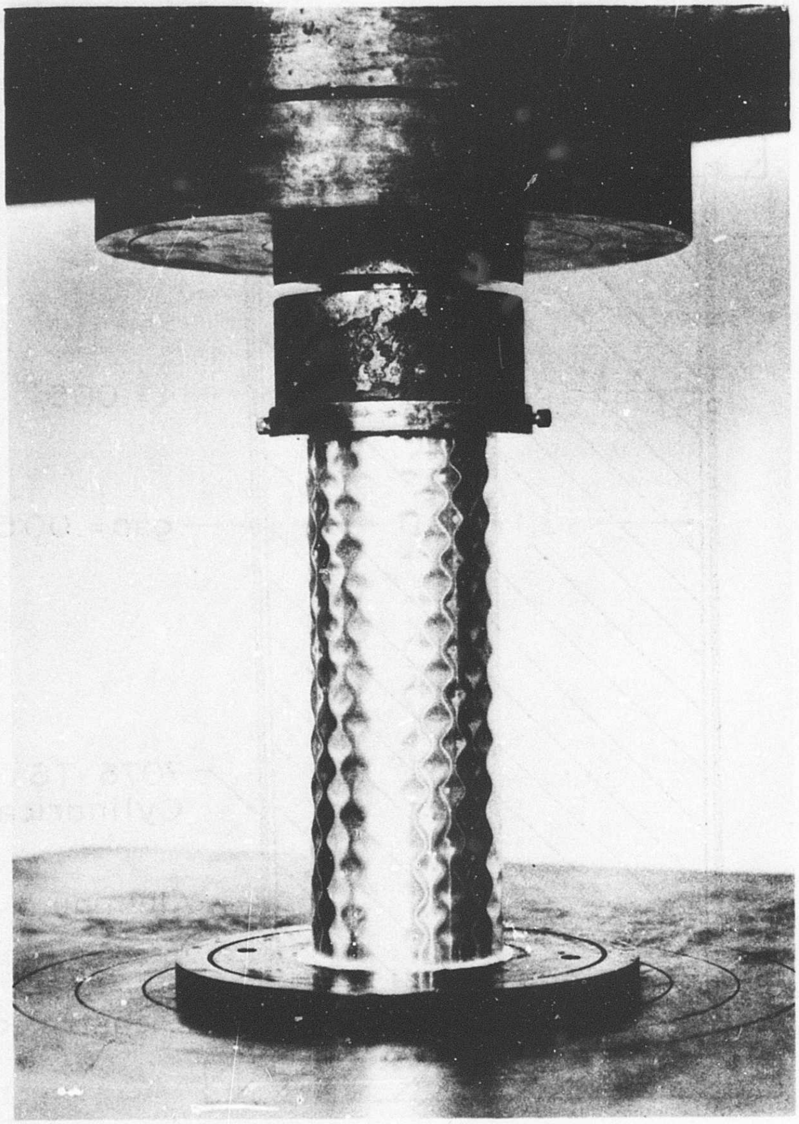

Figure 2. Cylinder Under Axial Compression with Completely Developed Buckle Patterns.

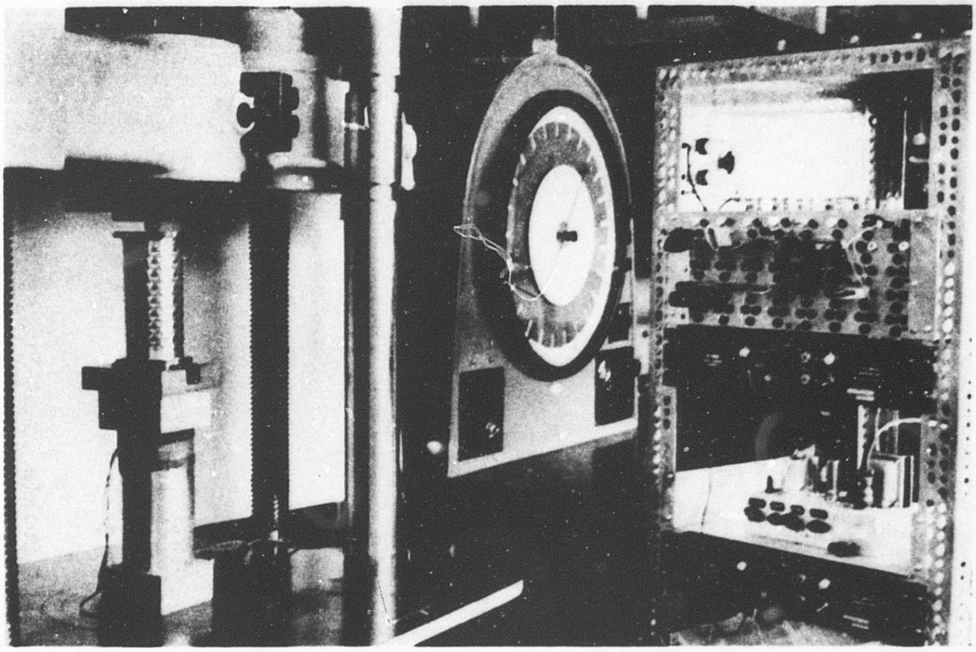

Figure 3. Experimental Setup Utilizing the Basic Thermal Ram in Conjunction with a Conventional Hydraulic Testing Machine.

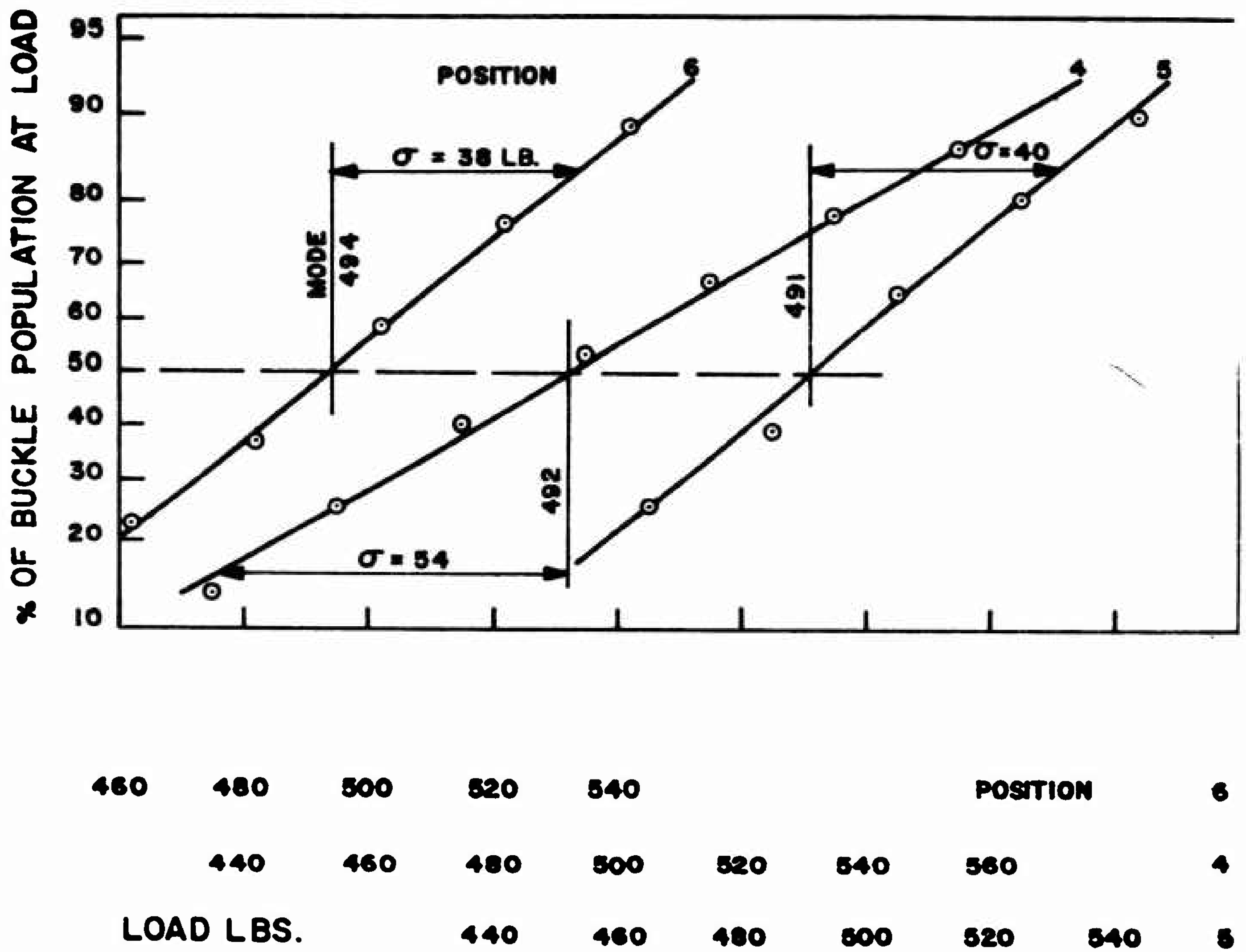

Figure 4. Typical Result of Buckle Count Proceeding from a Circular Cylindrical Shell Under Combined Loading of Flexure and Axial Compression.

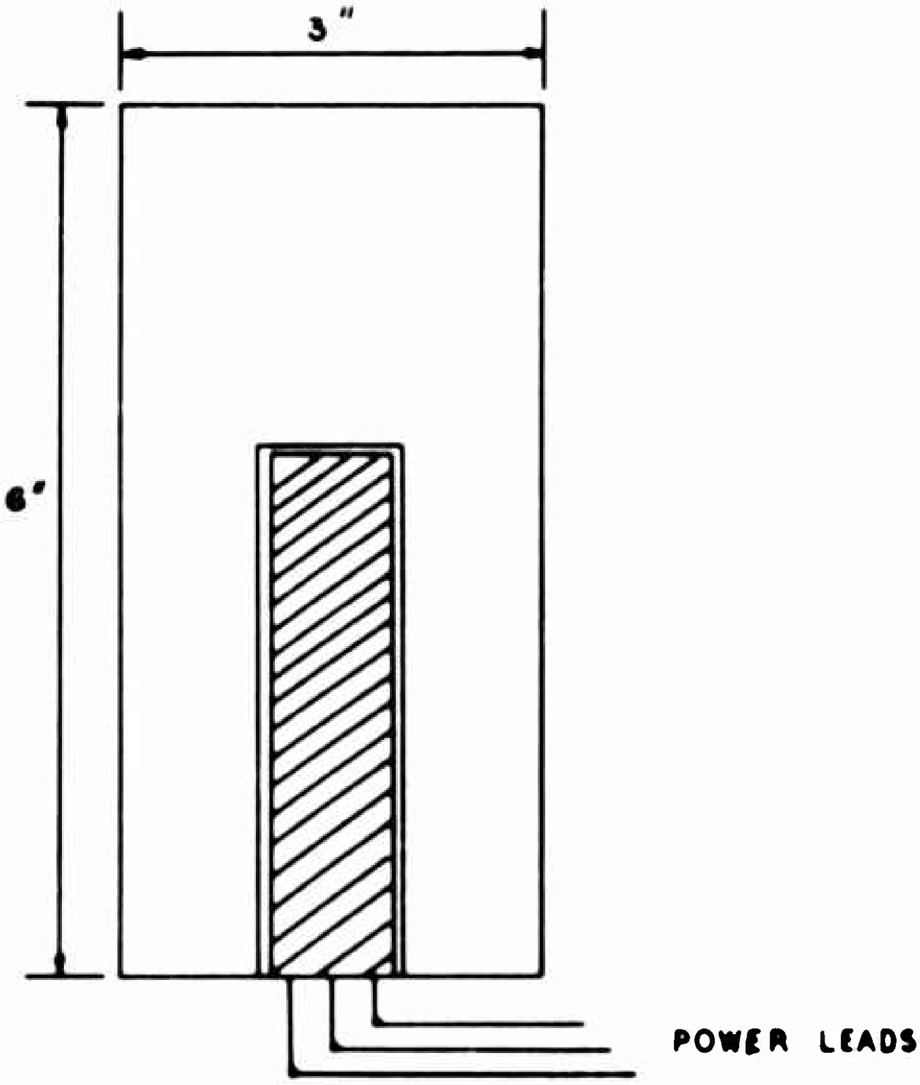

Figure 5. Cross Section of the First Thermal Ram Showing the Single Cartridge Type Heater Inserted in a Circular Aluminum Block.

A TEST MACHINE BASED ON THE THERMAL RAM PRINCIPLE

The first test machine specifically designed around the thermal ram is shown in Figure 6. It was made by modification to a hydraulic machine. Since this device was constructed primarily for system evaluation, it is only fair to record that the full potential of the principle was not realized. However, a very satisfactory and quite inexpensive machine has resulted; thus, it seems warranted to describe the basic design. The thermal ram used is shown in cross section in Figures 7 and 8. It was an aluminum rod 14 inches in length and 3 inches in diameter. The heat source was a combination of heater tape on the outside of the block and cartridge heaters centrally located. A total power of 2100 watts was provided in order that high strain rates could be achieved. Cooling of two types was used. The first system was employed to maintain the steel loading head at constant temperature. The purpose of the second was to tighten the control loop and simultaneously provide two-way loading action. Overall power control was obtained via a relay system and a feedback loop as diagrammed in Figure 9. With the system outlined, it has been found possible to produce controlled end shortening up to rates of 0.005 inch per minute. The stability for a given end shortening has been demonstrated to be excellent. The average temperature of the ram can easily be kept stable to within $\pm$ 0.1 degree Fahrenheit; consequently, the end shortening can be maintained to within $\pm$ 12 μ inches. This variation is clearly not significant in any practical application. Due to the fact that the thermal masses of the heater system and the ram are widely different - heater thermal mass/ram thermal mass being of the order 250 - there is very little overshoot when heater current is reduced or turned off, and the overshoot which is experienced can be readily compensated by the cooling fluid.

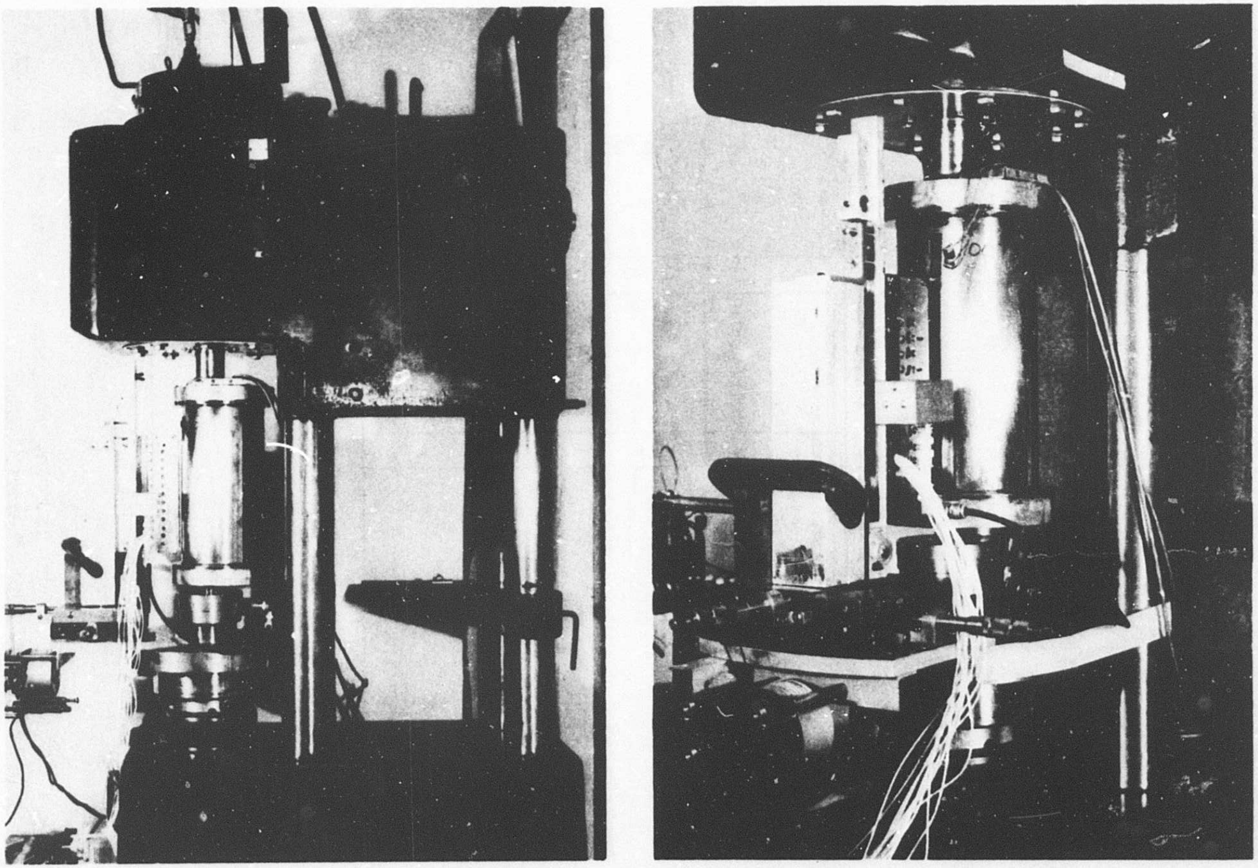

Figure 6. Pictorial View of the First Testing Machine Specifically Designed Around the Thermal Ram Concept.

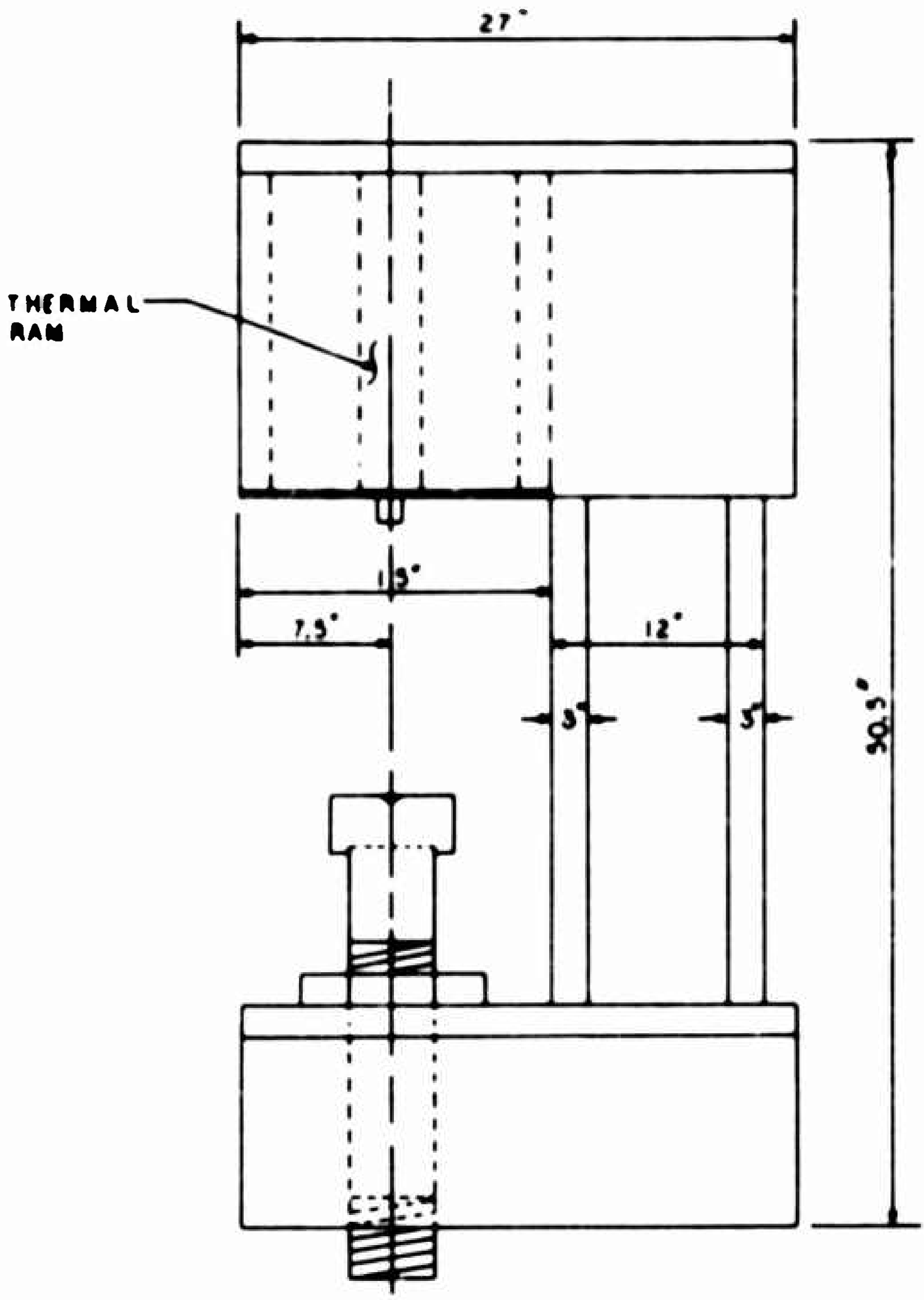

Figure 7. S:le View of the Testing Machine Showing the Location of the Thermal Ram.

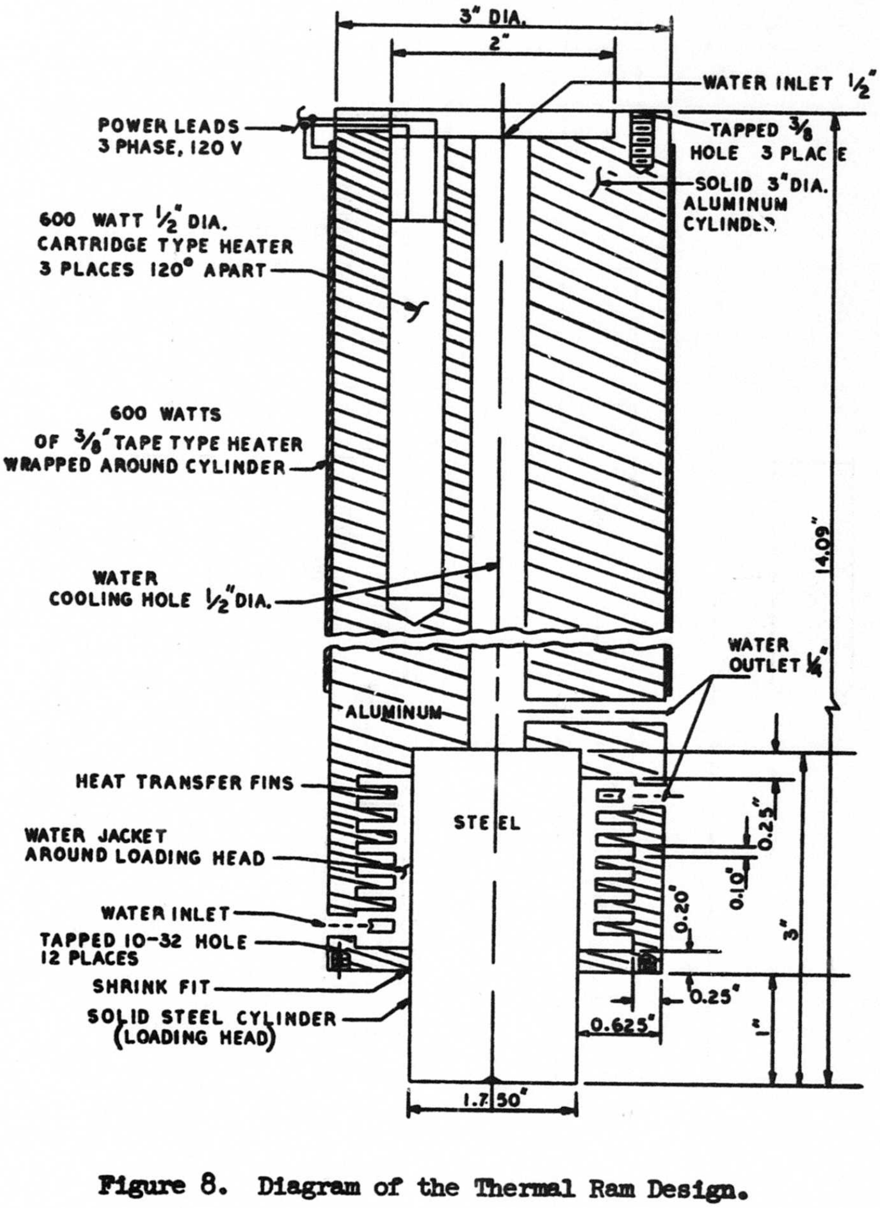

Figure 8. Diagram of the Thermal Ram Design.

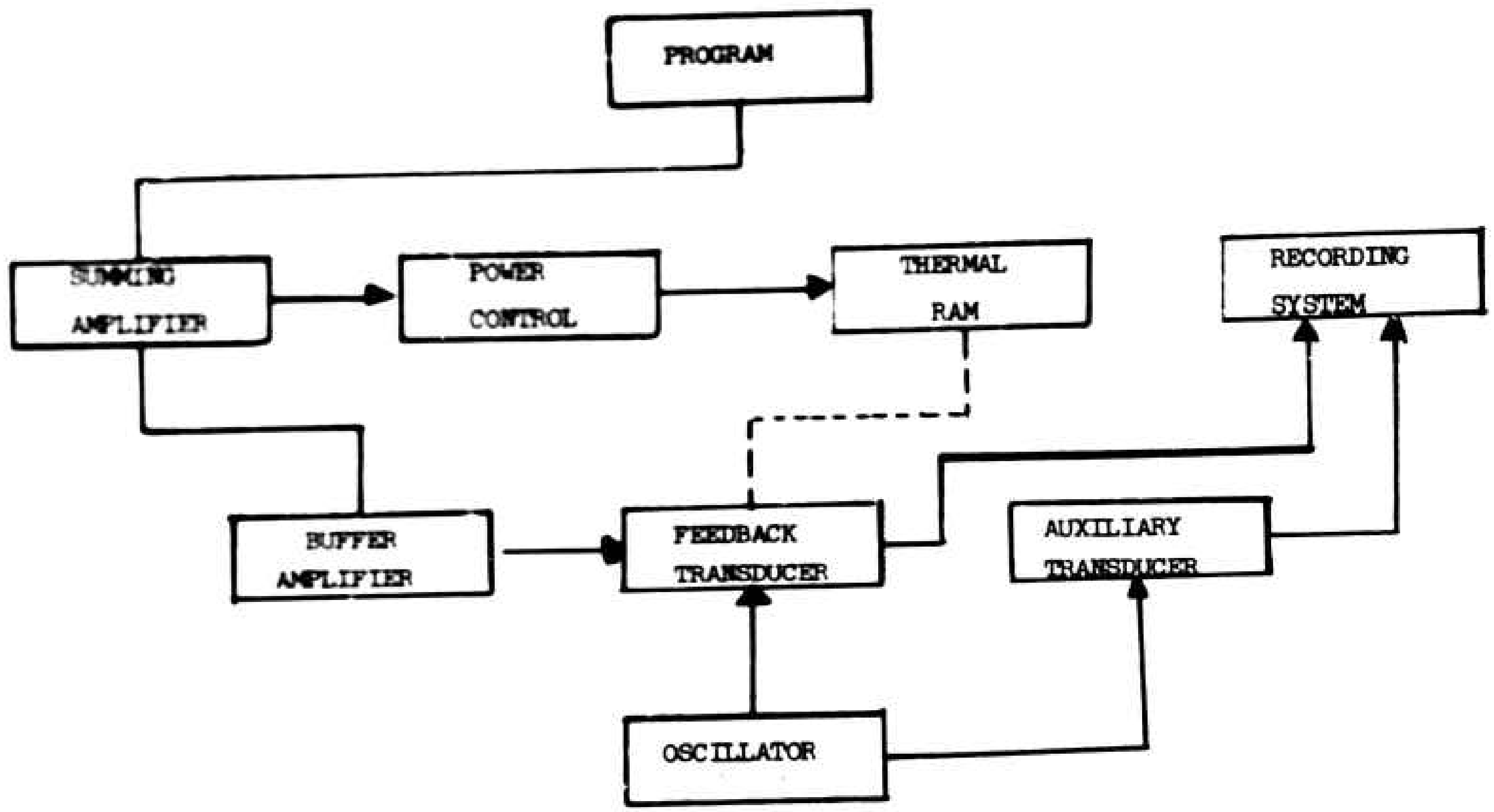

Figure 9. Block Diagram of the Thermal Ram Instrumentation and Control System.

A UNIQUE TEST SYSTEM BASED ON THE THERMAL RAM CONCEPT

There has been considerable study of an analytical kind with regard to the influence of edge conditions on the instability of compressed circular cylinders. There has been little experimental work in this area due to the basic difficulty in such operations. Babcock and Sechler (Ref. 4) made a very interesting laboratory study, but so far as we have been able to ascertain, this work stands alone. A perusal of this work shows clearly the difficulty of the problem. The thermal ram concept discussed in this report provides a very elegant approach to be made to the specific aspect of the influence of the boundary restraint against Poisson expansion. As noted in the introductory remarks, when a block of uniform material is raised to a constant temperature, it expands in all directions, the expansion in each direction being proportional to the appropriate linear dimension. Thus, if we are concerned with a circular bar of expansible material, we can achieve any ratio of longitudinal to radial expansion we desire by choosing the appropriate relation between length and diameter. Hence, it is clear that the thermal ram concept can be applied to the study of shells in which various degrees of end radial motion are achieved. There is, of course, a minor complication: unless the shell material is invar, a material with zero expansivity and virtually no change in modulus over the normal temperature range, unwanted thermal stresses are induced. However, if invar is used, and good shells can be machined from this material, the research possibilities are most interesting. Currently, an experiment based upon this process is under way. The results will be reported in a subsequent report.

APPLICATION TO NONUNIFORM LOAD STUDIES

The thermal ram may be designed with a cross section which is triangular or square instead of circular. In fact, the shape of the cross section may be designed in such a manner as to obtain a nonuniform expansion of the ram cross section for a constant heat input per unit area, Figure 10. Using this property, a thermal ram loading system may be manufactured which can apply precise nonuniform loads at strain rates orders of magnitude below those provided by conventional test machines. Moreover, its restrictions in size results only from considerations of stability. Thus, many very small rams, designed to remain stable under the expected loads, may be positioned and individually expanded on a structure to obtain a wide variety of nonuniform loading conditions, Figure 11.

A loading system designed with the ideas given above coupled with load and motion transducers of high sensitivity and resolution which are insensitive to thermal environment allow precise load programs to be achieved by closed loop servo control of the thermal ram expansion. Such transducers have been developed based upon capacitive principles and are described fully in a forthcoming report.

A schematic of a nonuniform loading system is given in Figure 10.

A practical method for achieving uniform distribution of compressive load for panel testing is depicted in Figure 11. This is essentially an automation of the technique described by Hoff, et al, in Reference 5.

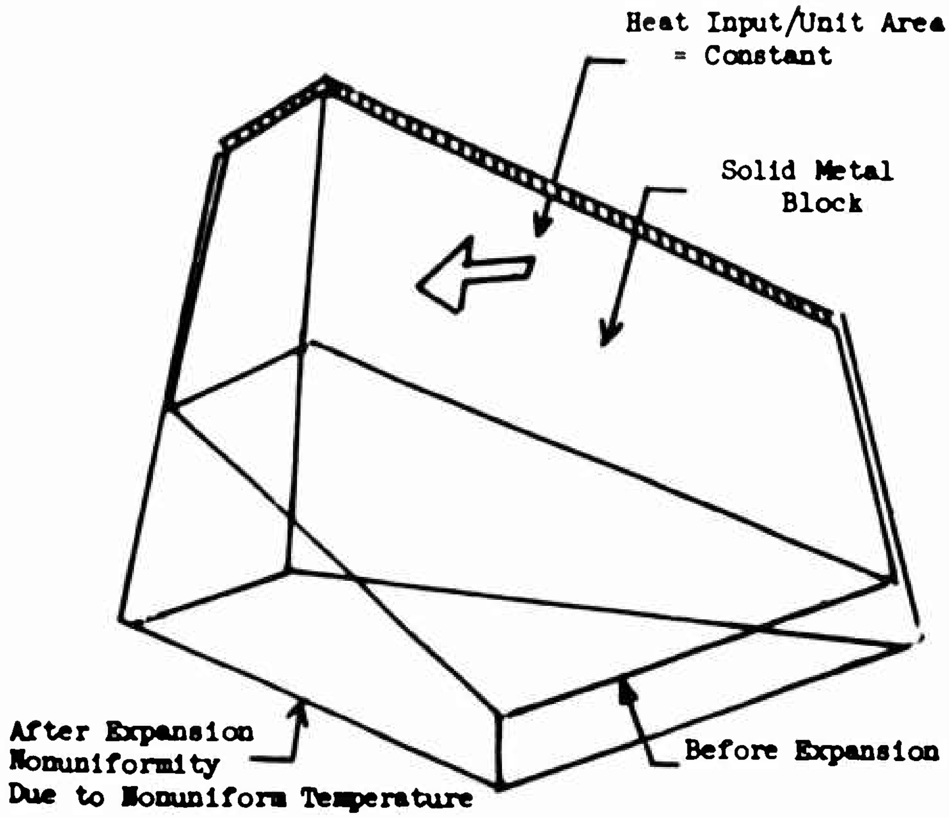

Figure 10. Method of Obtaining Nonuniform Loading.

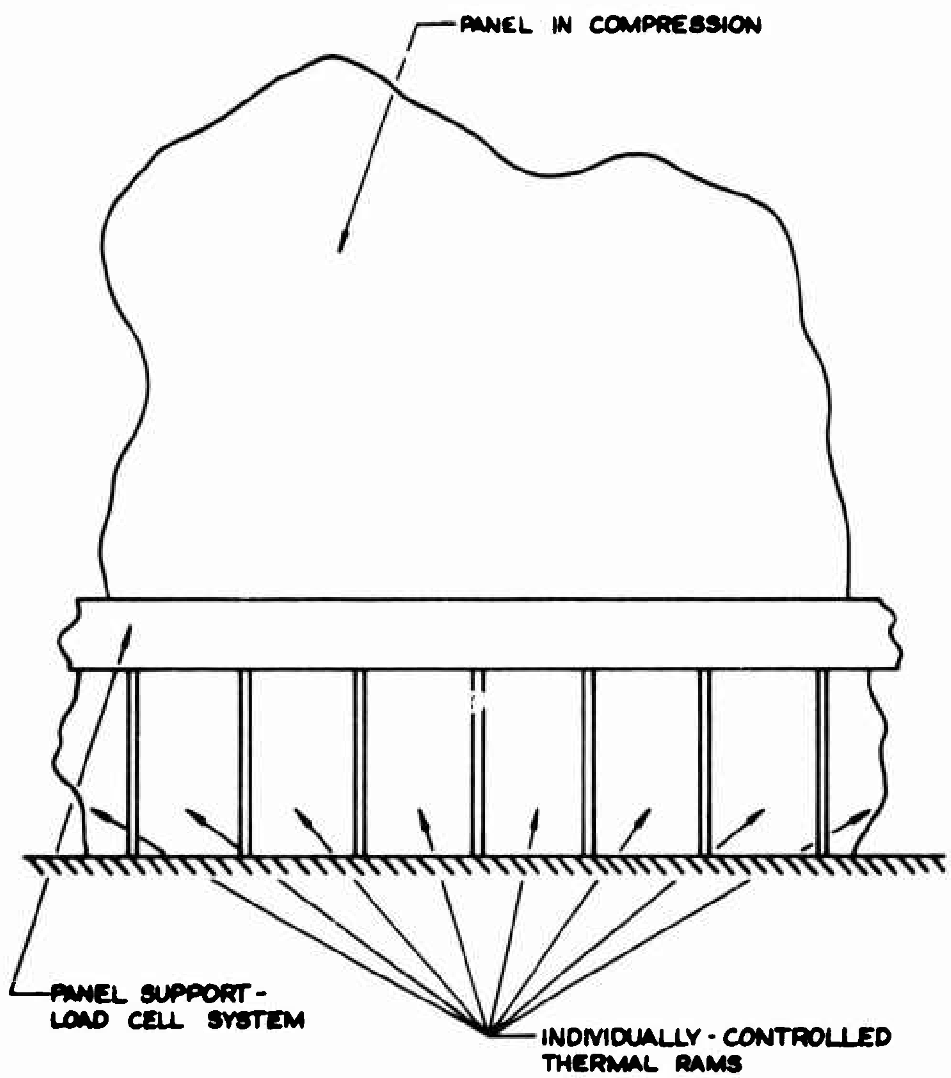

Figure 11. Method of Obtaining Local Load Variation in Panel Tests Using the Thermal Ram Concept.

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APPENDIX

CONTROL SYSTEMS FOR THERMAL RAM DEVICES

The great advantages of thermal ram systems are the lack of mechanical complexity and the consequent ease of manufacture. These advantages would, however, be lost if the control system required were too involved. Fortunately, this is not the case. In fact, in many instances, thermal ram systems lend themselves ideally to the most elementary types of control devices.

The simplicity results from the fact that thermal expansion is actually a second-order effect of heating. Thus, a very rough heat input will be substantially smoothed, and the resulting end shortening will be comparatively uniform.

The need is for automatic regulation of an electrical power supply. There are many common ways in which this may be accomplished. The method chosen must depend primarily on the degree of refinement required in a particular application.

The most rudimentary of all control techniques is the so-called "bang-bang" or contactor device. More advanced systems include: rheostats in series, auto transformers, thyratrons, saturable core reactors, and several of the newer solid-state devices. It is not appropriate to describe these systems in this report since they are all essentially standard processes and, in general, stock items from manufacturers.

It is, however, pertinent to discuss the considerations involved in selection of a power control method. Two examples will be given.

The original thermal ram was designed so that it would have an unusually high thermal mass and consequent high damping; therefore, a contactor control system could be used. The thermal mass of the ram (see Figure 8) is

$$\rho CV = 0.1 \frac{\text{lb}}{\text{in.}^3} \times .23 \frac{\text{BTU}}{\text{lb}^\circ\text{F}} \times 99 \text{ in.}^3 = 2.3 \frac{\text{BTU}}{^\circ\text{F}}$$

and the maximum available power is 2100 watts. Therefore, in the ideal condition (very closely approximated), we would expect an end shortening rate given by

$$\text{End shortening rate} = \frac{\alpha LW}{\rho CV} = \frac{13 \times 10^{-6} \frac{1}{^\circ\text{F}} \times 14 \text{ in} \times 2.1 \text{ kw}}{2.3 \frac{\text{BTU}}{^\circ\text{F}} \qquad \frac{1.05 \text{ kw-sec}}{\text{BTU}}}$$

$$= \underline{158 \times 10^{-6} \text{ in/sec}}$$

If we are attempting to maintain a constant end shortening and the contactor control system has a response time of .1 sec (cycle time of

relay), then we would anticipate the machine to have a "dither" or hunt around the set point of about 16μ inches for an ideal (no hysteresis) control technique.

The scheme used in the prototype machine achieves a dither of about 30μ inches. The degradation is due to control hysteresis and could definitely be improved.

However, this method is satisfactory in some applications; for instance, instability tests on fiber glass shells of .010 inch wall thickness, 4-7/8 inches OD, and 10 inches length. Such bodies require end shortening of the order of .020. The "dither" amounts to only .15% of the total deflection. For these tests, this is almost certainly satisfactory.

For metal shells, for instance, .003 inch thick, 3 inches in diameter, and 9 inches long, a dither of much lower magnitude is necessary. Fortunately, lower end shortening rates are also appropriate, and so the power level can be reduced to 700 watts (by disconnecting two of the phases). The hunting is proportionally smaller (10μ inches), which is about the same as that of the best hydraulic machines.

As an example of a thermal ram in which a contactor control system would not be satisfactory, consider the model shown in Figure 12. This has the following material and geometric characteristics:

<u>Ram Cylinder Geometry</u>:

Diameter - 10 inches; thickness-0.200 inch; length-20 inches
Ram Material - Aluminum
Ram Heaters - Blanket type, inside and outside. Power:
10 watts/inches^2. Total power: 12 kw

For this model, the thermal mass is $\rho CV = 2.25 \frac{\text{kw-sec}}{^{\circ}\text{F}}$. This gives a maximum end shortening rate of .00125 inch per second. It is quite obvious that a constant end shortening could not be maintained without a proportional control system. For this ram, a silicon controlled rectifier device would be highly appropriate.

If extreme control is required, attention should be given to the effect of the power excitation frequency. For instance, if the ram discussed were powered by a single phase silicon control rectifier, dither of 23μ inches at 60 cps would occur if the heat transfer system were ideal. If this is too great, a d.c. excited system would be required, and this would be controlled by a bank of high power transistors.

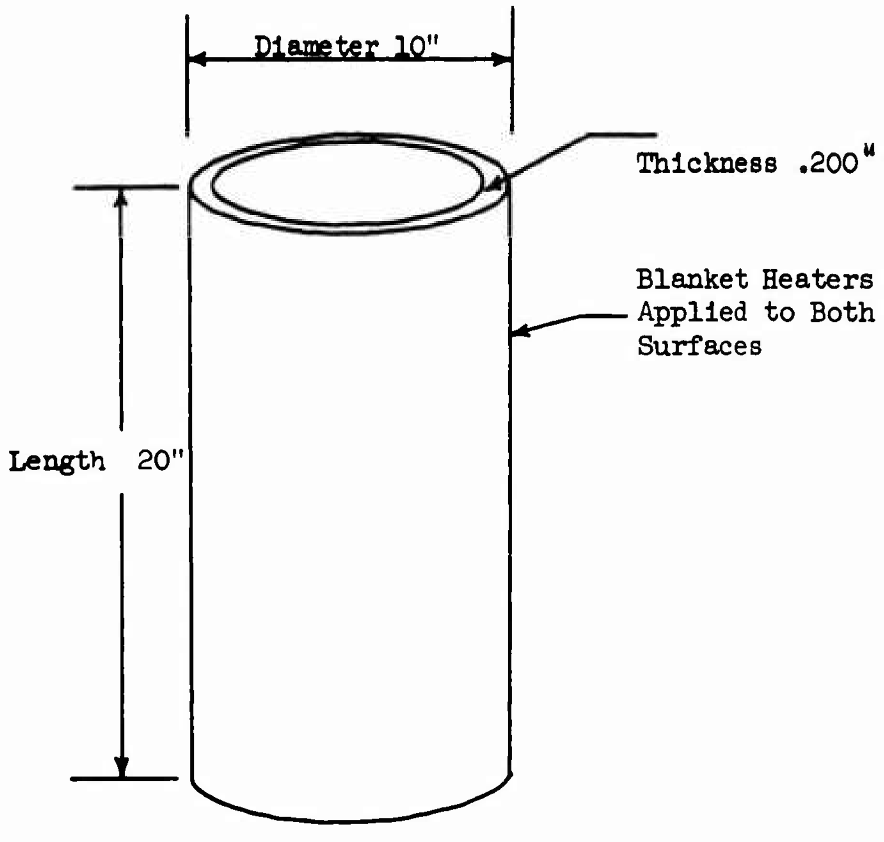

Figure 12. Thermal Ram Model Used in Example.

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Test Machine						
Instability Studies						
Boundary Conditions						

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